EXPERIMENTAL STUDY OF FORMABILITY OF SHEET METAL IN DEEP DRAWING PROCESS

MUHAMMAD SAFWAN BIN ISMAIL

BACHELOR OF ENGINEERING

UNIVERSITI MALAYSIA PAHANG

2010

ABSTRACT

One of the most common outcomes in deep drawing process is a cup fractures that occur at the bottom of the cup shell. This cup fracture is cause by many parameters like blank holder force (BHF), blank diameter, friction between punch and blank, normal anisotropy of material, blank thickness and many more. The main objectives of the present study is to find the value of limiting drawing ratio (LDR) in LDR test and to predict the forming limit behaviour of sheet metal in deep drawing by construct a forming limit diagram (FLD) in FLD test for both aluminium AA1100 and copper. To determine the drawability of aluminium AA1100 and copper, LDR test with variable of blank diameters (80mm, 85mm, 90mm, 95mm and 100mm) and two set of BHF (with spring constant is 16.3 N/mm and 10 N/mm) was utilized. On the other hand, the parameters that have used in FLD test is variable of blank thickness (1mm and 0.6mm) and surface condition of a blank using aluminium AA1100 as a constant material. In surface condition of a blank, a lubricant have been added to investigate the effect of friction between blank and punch in deep drawing process. It is observed that higher blank diameter and BHF raises the value of LDR and thus increases the drawability of aluminium AA1100 sheet and copper sheet. For FLD test, the level of FLD is increasing with increasing of blank thickness of aluminium AA1100. Besides that, the present of lubricant also raised the level of FLD and thus lessen the tendency of aluminium AA1100 sheet to rupture. From both of the experiment, it can be concluded that the formability of sheet metal is increasing due to increasing of blank diameter, blank thickness, BHF and present of lubricant. Besides that, the formability of aluminium AA1100 sheet is better compare to copper sheet.

ABSTRAK

Salah satu hasil yang paling umum berlaku dalam penarikan dalam adalah keretakan cawan yang berlaku di bahagian bawah kulit cawan. Keretakan yang berlaku pada cawan ini disebabkan oleh pelbagai parameter seperti daya penahan bahan (BHF), diameter bahan, geseran antara penumbuk dengan bahan, anisotropi bahan, ketebalan bahan dan sebagainya. Objektif utama penyelidikan ini dijalankan adalah untuk mencari nilai nisbah penarikan terhad (LDR) di dalam ujian nisbah penarikan terhad dan juga untuk meramalkan perilaku had pembentukan lembaran logam dalam proses penarikan dalam dengan membina gambarajah had pembentukan lembaran logam (FLD) di dalam ujian FLD untuk kedua-dua bahan yang digunakan iaitu aluminium AA1100 dan juga kuprum. Untuk mengkaji keboleh tarikan lembaran logam aluminium AA1100 dan juga kuprum, ujian LDR telah dijalankan dengan menggunakan pemboleh ubah diameter bahan (80mm, 85mm, 90mm, 95mm dan 100mm) dan juga dua set BHF (dengan kemalaran spring 16.3 N/mm dan juga 10 N/mm). Di sudut yang lain pula, parameter yang telah digunakan di dalam ujian FLD adalah ketebalan lembaran logam (1mm dan 0.6mm) dan juga keadaan permukaan bahan dengan menggunakan bahan yang sama iaitu aluminium AA1100. Untuk keadaan permukaan bahan, satu pelincir telah digunakan bagi menyiasat kesan geseran antara lembaran logam dan juga penumbuk dalam proses peanarikan dalam. Daripada ujian LDR yang telah dijalankan, ianya dapat diperhatikan yang pengunaan diameter bahan yang besar dan juga BHF yang tinggi dapat meninggikan lagi keboleh tarikan lembaran logam aluminium AA1100 dan juga kuprum. Untuk ujian FLD, tahap sesebuah FLD akan meningkat sekiranya ketebalan lembaran logam aluminium AA1100 yang digunakan juga meningkat. Selain daripada itu, kehadiran pelincir juga akan meningkatkan lagi tahap FLD lembaran logam aluminium AA1100 seterusnya menunjukkan kecenderungan lembaran logam aluminium AA1100 untuk retak juga akan berkurang. Daripada pemerhatian kedua-dua eksperimen yang telah dijalankan ini, ianya dapat disimpulkan bahawa keboleh bentukkan lembaran logam sesebuah logam akan meningkat sekiranya diameter yang besar, ketebalan yang tinggi, BHF yang tinggi dan juga kehadiran pelincir digunakan. Selain daripada itu juga, keboleh bentukkan lembaran logam aluminium AA1100 juga adalah lebih tinggi berbanding lembaran logam kuprum.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION TO DEEP DRAWING PROCESS

Deep drawing process is a sheet metal forming process where a punch is utilized to force a flat sheet metal to flow into the gap between the punch and die surfaces. As a result, the sheet metal or blank will deformed into desired shape like cylindrical, conic, or boxed-shaped part and also complex parts which normally require redrawing processes by using progressive dies. Deep drawing is a popular selection due to its rapid press cycle times. Its capability of producing complicated shaped and geometries with low labours requirement is also an advantage in manufacturing industries (Boljanovic, 2004). A few examples of deep drawing applications that is widely use nowadays include beverage cans, automotive bodies, aircraft panels and sinks.

The important variables which affect the formability of sheet metal in deep drawing process can be divided into two categories: Material and friction factors; and tooling and equipment factors. With the right and proper selection of these variables, the formability of the material can be process at its optimum result and reducing the defects in deep drawing process like fracture, wrinkling and earing (Tzou et al., 2007).

Sheet metal forming process is used for both serial and mass production. Their characteristics are high productivity, highly efficient use for material, easy servicing machines, the ability to employ workers with relatively less basic skills and other advantageous economic aspects. Part that made from sheet metal has many attractive qualities: Good accuracy of dimension, adequate strength, light weight and a broad range of possible dimensions (Boljanovic, 2008).

1.2 PROBLEM STATEMENT

In many cases after the sheet metal was successful draw in deep drawing process, the fracture at the shell of the specimens always occurred and thus cause the defects on the product. It is one of the most common undesired outcomes in deep drawing because if this happen, the product is in defects condition and the deep drawing process must be redone again using another specimen. This fracture is caused by excessive punch force, excessive blank holder force, excessive friction between blank and tooling, insufficient clearance between punch and die and insufficient punch or die corner radius. Hence, many experimental work that have been done lately to prevent or reduce this fracture when running a deep drawing process. The common method that have been use to investigate the formability of sheet metal in deep drawing process is by calculate the limiting drawing ratio (LDR) of sheet metal to investigate their drawability and the other method is by construct the forming limit diagram (FLD) of sheet metal to predict their formability behaviour during deep drawing operations.

1.3 PROJECT OBJECTIVES

1) To investigate the effect of variable blank diameter and blank holder force on LDR for aluminium AA1100 and copper.
2) To predict the forming limit of aluminium AA1100 with variable of blank thickness and effect of lubricant by construct the FLD diagram.

1.4 SCOPES OF THE PROJECT

1) To conduct an experimental study of deep drawing process by using a deep drawing machine with supported of hydraulic press machine.
2) The punch diameter that was used is 50 mm with punch and die corner radii of 6.36 mm.
3) Blank material that was used is aluminium AA1100 and copper that is widely uses nowadays in deep drawing process.
4) Blank diameters that was used is 80 mm, 85 mm, 90 mm, 95 mm and 100 mm in LDR study.

5) Blank diameter was cut using electric discharge machine (EDM) wirecut because of its cutting precise.
6) The blank holder force that was used in present study is 16.3 N/mm and 10 N/mm.
7) Blank thickness is 1 mm and 0.6 mm with the diameter of 95 mm for Aluminium AA1100 in FLD study.
8) The diameter of circle grid that was used in FLD test is 2 mm according from previous studies.
9) Lubricant that was used in LDR and FLD test is Lithium grease.

CHAPTER 2

LITERATURE REVIEW

2.1 SHEET METAL

Sheet metal is one of the most important semi finished products used in the steel industry, and sheet metal forming technology is therefore an important engineering discipline within the area of mechanical engineering. Sheet metal is characterized by high ratio of surface to thickness. Sheet metal forming is basically conversion of flat sheet metal into a product of desired shape without defect like fracture or excessive localised thinning (Gardeen and Daudi, 1983).

The products made by sheet metal forming processes include a large variety of shapes and sizes, ranging from simple bends to double curvatures with shallow or deep recesses. Typical examples are metal desks, appliance bodies, aircraft panels, beverage cans, auto bodies, and kitchen utensils. In many cases while deforming the sheet metal, the component fractures at certain point. The causes of failure are parameters related to forming process. The sheet metal is available as flat pieces. The sheet metals are formed by running continuous sheet of metal through a roll slitter. The sheet metal thickness is called gauge and the gauge of sheet metal ranges from 30 gauges to 8 gauges. The thinner the metal is, the higher of gauge.

There are many application that using sheet metal like car bodies, airplane wings, roofs, lab table and many more. In automobiles the sheet metal is deformed into the desired and brought into the required form to get car part body pressings like bonnet, bumpers, doors, etc. In aircraft's sheet metal is used for making the entire fuselage wings and body. In domestic applications sheet metal is used for making many parts like washing machine body and covers, iron tops, timepiece cases, fan blades, cooking utensils and etc.

2.2 DEEP DRAWING PROCESS

Deep drawing is a manufacturing process of forming sheet metal stock, called blanks, into geometrical or irregular shapes that are more than half their diameters in depth. Deep drawing involves stretching the metal blank around a plug and then moving it into a moulding cutter called a die. Common shapes of deep drawn products including cylinders for Aluminium cans and cups for baking pans. Irregular items, such as enclosure covers for truck oil filters and fire extinguishers, are also commonly manufactured by the deep drawing method.

The drawing of sheet metal or commonly known as deep drawing is a process which a punch is used to force a sheet metal to flow between the surfaces of a punch a die. As a result, a cylindrical, conical or box-shaped part is formed in the die with minimal material scrap (Boljanovic, 2004). In this process, a flat sheet metal was kept under a blank holder force (BHF). The blank holder should allow the material to slide into the die surface but at the same time, that force must be a great enough to prevent wrinkling of the sheet as it drawn as shown in Figure 2.1. The punch transferred the force through the punch and thus the punch transmits the force through the walls of the cup as it drawn into the die cavity (Singh, 2008).

In deep drawing process, it can be divided into two types that is pure bending and ironing. Pure bending is type of deep drawing without a reduction in the thickness of the workpiece material while in ironing, it a deep drawing with a reduction in the thickness of the workpiece material (Boljanovic, 2004). A schematic illustration of these two types of deep drawing is shown in Figure 2.2. From the Figure 2.1, it is clear that the basic tools for deep drawing are the punch, the drawing die ring, and the blank holder. However, some products cannot be drawn in a single draw and requires secondary drawing that is redrawing process. As a result, the design of the die will be more complicated as a progressive die is normally required to allow multiple drawing operations under one production line.

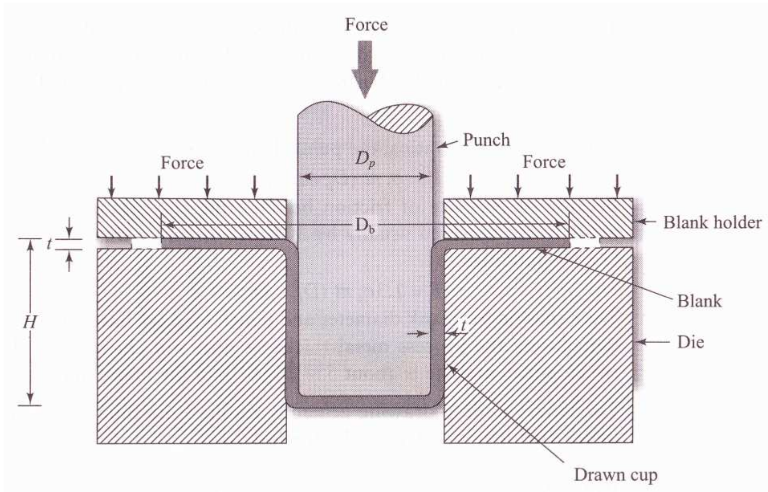


Figure 2.1: A deep drawing operation

Source: Singh, 2008

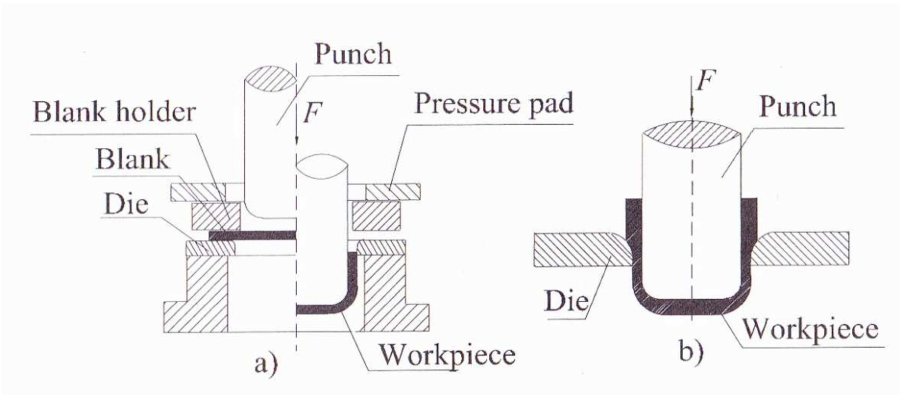


Figure 2.2: Schematic illustration of deep drawing process: (a) Pure Bending; (b) Ironing

Source: Boljanovic, 2004

A percentage reduction of 48% is considered excellent on the first draw. Succeeding draws are smaller. There should be no appreciable change in the thickness of the material between the blank and the finished part.

Results of deep drawing are mostly empirical in nature and research has been done only limited almost exclusively to the drawing of cylindrical cup. For other shapes theoretical analysis is too much complicated and has no practical significance (Singh, 2008).

In deep drawing process, there are several factors that can be affected the process which are categorized into two groups: Material and friction factors, and tool and equipment factors. Thus it is important before running the deep drawing process, these factors was considered well to prevent an undesirable result like earing, fracturing, and wrinkling.

In Figure 2.3, it shows clearly these two factors (material and friction, tool and equipment) that need to consider in deep drawing process. Recently more studies have been develop by refer to these factors in order make an improvement while running deep drawing process.

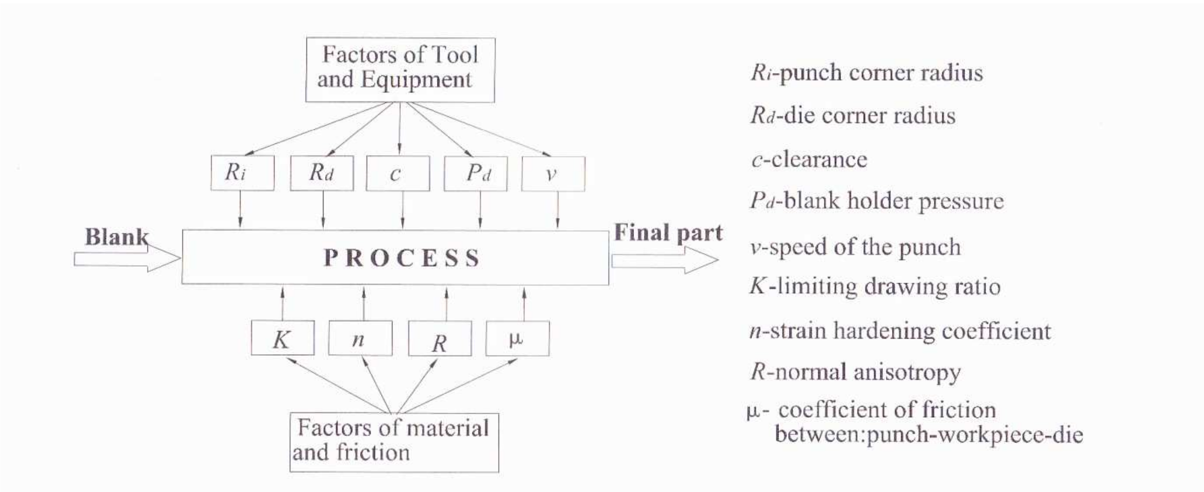


Figure 2.3: Significant variables in deep drawing

Source: Boljanovic, 2004

2.3 FORMABILITY TEST

Sheet metal formability is undergoing a transition from art to science. Formability within each forming mode can be related to specific metal formability parameters. The successful sheet metal forming process which is can be converts initially from flat to desired shape. There are many major failures that always happened such as splitting, wrinkling or shape distortion. The formability test is use to access of sheet to be deformed into useful part (Wick et al., 1998).

The testing can be divided into two types: Intrinsic and simulative. The intrinsic tests measure the basic material properties under certain stress strain states, for example the uniaxial tensile test and the plane strain tensile test. Traditional evaluation of formability is based on both intrinsic tests and simulative tests. The intrinsic tests measure the basic characteristic properties of materials that can be related to their formability. These tests provide comprehensive information that is insensitive to the thickness and surface condition of the material. Examples of intrinsic tests are Hydraulic Bulge test, Marciniak In-Plane Sheet torsion test, and Miyauchi shear test. The simulative test can provide limited specific information that may be sensitive to factors other than material properties like the thickness, surface condition, surface lubrication and etc. Subject the material to deformation that closely resembles the deformation that occurs in a particular forming operation. Examples of these tests include Ericksen, Olsen, Fukui and Swift Cup Tests (Wagoner and Chenot, 2001).

2.4 SHEET METAL FORMING IN SWIFT CUP TEST

The Swift Cup test is usually considered to provide a measure of the drawability of sheet metal. A schematic representation in Swift Cup test is shown in Figure 2.4. A disc-shaped sheet specimen of metal is placed between the blank holder and the die and then it is drawn into a cup by a cylindrical punch. A cup with a cylindrical shape will be form after that. Various shapes were proposed by Swift for the bottom of the punch, but in the present study only flat-ended punches will be consider (Budiansky and Wang, 1966).

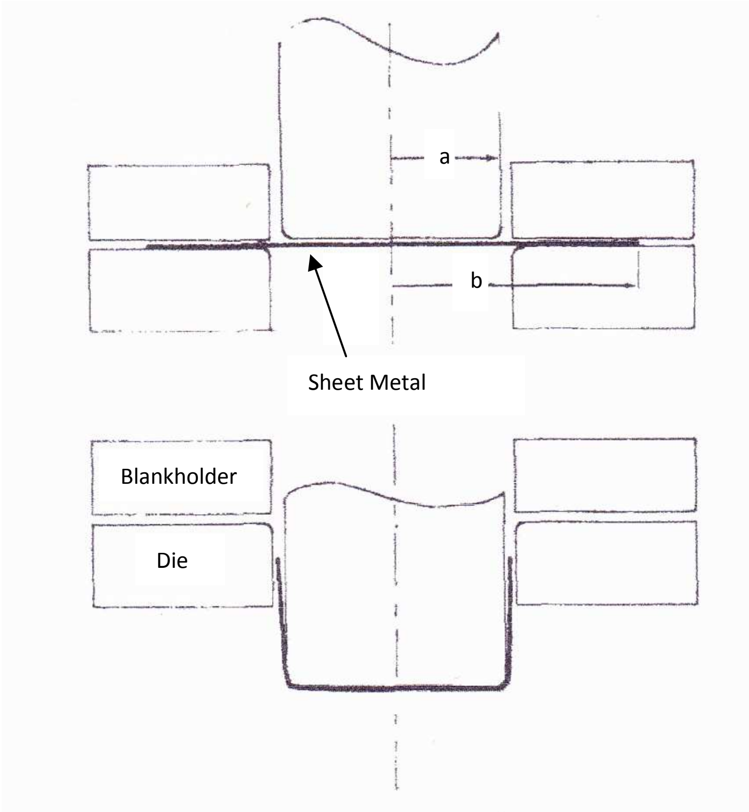


Figure 2.4: Schematic representation of Swift cup test

Source: Budiansky and Wang, 1966

Let the radius of the punch and the radius of the specimen be *a* and *b* respectively. Then the ratio between these two radius that also known as drawing ratio, can be write as *b*/*a*. One of the principal objectives of the Swift Cup test is to determine the limiting drawing ration, LDR which is defined as the largest drawing ratio from which a cup can be drawn without fracture. The better drawing materials are recognized as those having the higher LDR's.

The result in Swift Cup test is correlates well with the performance of sheet metal in deep drawing components. It can be tested with a variable size of sheet metal blank by increasing the diameter. The maximum blank size that can be drawn without fracture occurring over the punch nose can be uses to calculate the LDR's. Because the condition of the edge of each blank can have an important effect on the test result, the blank edges usually turned in a lathe to ensure strain-free, hurt-free edges (Khoruddin, 2009).

2.5 LIMITING DRAWING RATIO

The limiting drawing ratio (LDR), is commonly used to provide a measure of the drawability of sheet metal. The correlation of the LDR of a sheet metal with its material properties and process parameters has been activated by industrial necessity for improving drawability (Leu, 1999).

LDR is a ratio between the maximum blank diameter that can be drawn successfully to the cup diameter, is often taken measure as measure of drawability (Verma and Chandra, 2006). The drawability of sheet metal or LDR can be determined from different diameters of blanks with constant thickness. The LDR can be expressed as shown in Equation 2.1.

$$LDR = {}^{D_1}/_{D_o} \tag{2.1}$$

Where,

$D_0 =$ Maximum diameter of successful formation of cup

$D_1 =$ Initial blank diamater berfore drawing process

The blank diameter or sheet metal diameter is one of the most important parameter that have to consider in determine the LDR. Theoretically, the bigger the blank diameter it is, the higher value of LDR (Verma and Chandra, 2006). It means the blank with high value of LDR is a good material to consider in deep drawing process.

Many researchers have studied the effect of normal anisotropy, $\bar{R}$, and strain hardening exponent, *n*, on the limiting drawing ratio using either the experimental studies or the numerical models. The anisotropy is important in symmetrical draws was first shown by Whiteley (1960) and that research that has been done by Whiteley was used widely nowadays. Whiteley state that the LDR depends on $\bar{R}$. The higher $\bar{R}$, the better is the LDR. It was also concluded that LDR does not depend in any significant manner on the strain hardening exponent. Similar conclusions were also reached by several experimental investigations (Verma and Chandra, 2006).

Table 2.1: LDR values from previous studies

Material	**LDR (calculated)**	**LDR (experimental)**
Steel CA-DDQ	2.3025	2.1805
Steel BA-DDQ	2.2135	2.1805
Steel BA-CQ2	2.2575	2.1758
Mild Steels	2.4246	2.2486

Adapted from: Leu (1999)

Nevertheless, sheet metal with higher average strain value such as alpha-titanium are generally more desirable in deep drawing due to its higher formability. However, in actual applications, the price of the material needs to be considered to keep production cost realistic. In addition, the planar anisotropy also needs to be considered as it would affect the formation of ears.

Most of the deep-drawn products today are usually made of steel and aluminium alloys as they have higher formability and lower price compared to the other metals such as copper and tin. The high strength stiffness to weight ratio, good formability and good corrosion resistance of aluminium alloys make it an ideal candidate to replace heavier materials such as steel in fulfilling the weight reduction demand in automotive industry (Miller et al., 2000)

2.6 FORMING LIMIT DIAGRAM

2.6.1 Concept of Forming Limit Diagram

The concept of forming limit diagram (FLD) was introduced by Keeler (1965) and Goodwin (1968) which represents the first safety criterion for deep drawing operation. Marciniak and Kuczynski (M-K) have proposed a mathematical model for the theoretical determination of FLD that supposes an infinite sheet metal to contain a region local imperfection where heterogeneous plastic flow develops and localizes (Slota and Spisak, 2005). From FLD, the forming limit of sheet metal can be predicted by measured the reading of minor strain and major strain from the experiment and converted the data into FLD.

The FLD, which is consequently been widely referenced in the sheet metal forming industry is now a standard characteristic in the optimization of sheet metal forming processes. In FLD, the higher level of FLD can obtain, the more good of material that was used (Elangovan and Narayanan, 2010).

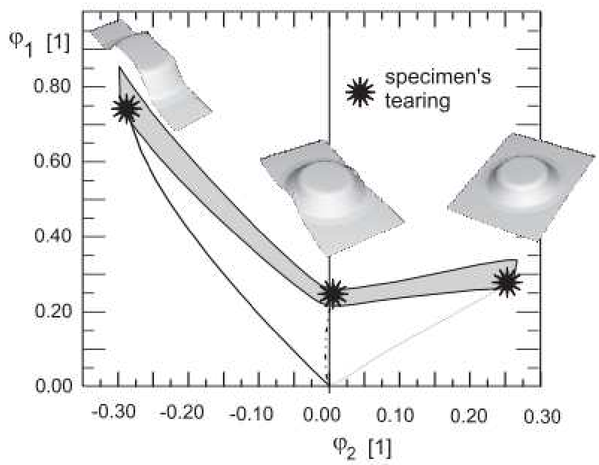


Figure 2.5: Example of FLD in sheet metal forming

Source: Pepelnjak and Kuzman, 2007

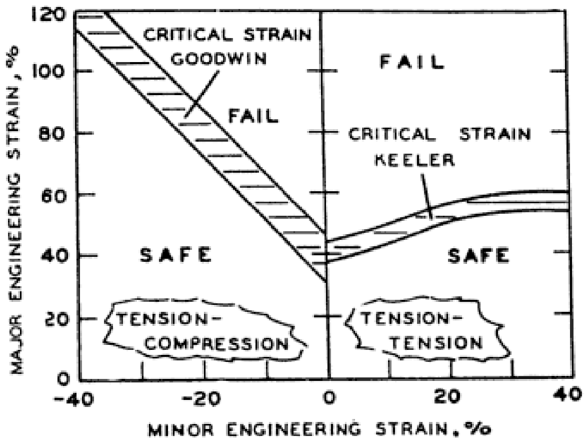


Figure 2.6: Forming limit diagram defined by Keeler and Goodwin.

Source: Banabic et al., 2000

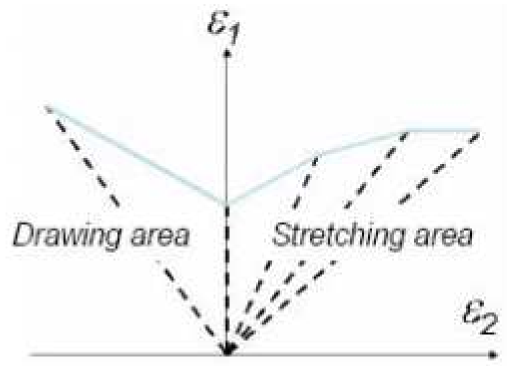


Figure 2.7: Forming limit diagram principle

Source: Chinouilh et al., 2008

The first pioneer works of the experimental determination of FLD by Keeler and Goodwin were followed by numerous research activities ranging from improved methods for experimental determination of FLD to analytical concepts allowing the calculation of FLD up to numerical approaches which are based on the simulations of various testing methods in digital environment (Pepelnjak and Kuzman, 2007).

Among several developed experimental tests, there are two experiments which have shown exceptional suitability for the evaluation of the entire range of FLD combined with simple tooling and experimental procedure that is Nakazima and Marciniak test. Marciniak (1973) has proposed a method for determination of the FLD with a flat punch (Banabic et al., 2000). The test tool consists of the drawing die, the blank holder and the punch. The punch has an even and partially sunk forehead. Various strain conditions are achieved by different widths of the analysed specimens which enable the determination of the entire range of FLD with one tool geometry only. During the testing procedure the even punch forehead causes the plane strain conditions in the analysed specimen area (Pepelnjak and Kuzman, 2007).

The FLD can be predicted by running the experiment on various types of sheet metal, the sheet metal thickness and with different value of BHF. Narayanasamy and Narayanan (2007) has done the test with variable blank thickness with IF steels as a material while Assempour et al. (2008) has done the experiment with variable size of diameter with ST12 low carbon steel as a material.

Table 2.2: Parameter that have been used in FLD experiment from previous studies

Material	Blank Diameter (mm)	Blank Thickness (mm)
IF Steels [1]	80	0.6, 0.9, 1.2, 1.6
Low Carbon Steels ST12 [2]	80, 90, 100	2.5

Adapted From: [1]Narayanasamy and Narayanan, 2007; [2]Assempour et al., 2008

2.5.2 Calculation for Forming Limit Diagram

The circle grid is the first methods that have been done by Keeler (1964) and Goodwin (1968) to evaluate the FLD. The circle grid will show the deformation of sheet metal after through the deep drawing process. The difference between diameter length of the circle before and after deformation can be recorded to evaluate the FLD. The major strain, ε_1 and minor strain, ε_2 of the blank can be calculated by using the formula as shown in Equation 2.2 and 2.3.

$$Major\ Strain, \varepsilon_1 = \frac{D_{1.cg(major)} - D_{0,cg(major)}}{D_{0,cg(major)}} \tag{2.2}$$

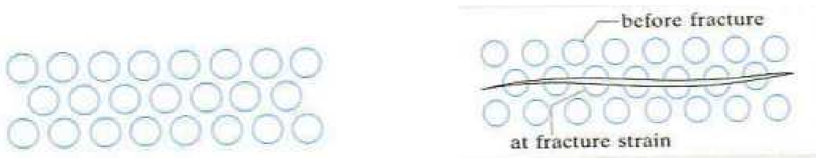
$$Minor\ Strain, \varepsilon_2 = \frac{D_{1,cg(minor)} - D_{0,cg(minor)}}{D_{0,cg(minor)}} \tag{2.3}$$

Where,

$D_0 =$ Diameter of circle grid before deformation (mm)

$D_1 =$ Diameter of circle grid after deformation (mm)

Before running the deep drawing process, the sheet metal or blank was marked with a close packed array of circles grid. This circle grid was important at the place where the deformation of sheet metal will deform because it can see clearly at that circle the deformation of the circle. Common length of circle grid that have been used in FLD test is ranging from 2mm to 8mm.



(a) (b)

Figure 2.8: Example of circle grid in FLD: (a) Before deformation; (b) After deformation

Source: Udomphol, 2007

Figure 2.8 show that a rupture of material after undergoes a deep drawing process. The rupture of the specimens occur because of the elongation of the material may pass the limit of its plasticity limit (Craig, 2000). The circles nearest to the fracture line gives the strain ratio at the critical point (Schey, 2000).

When the die is punch the blank into desired shape, the deformation of the circle grid will resulting the stretching the circles into ellipse. The circle grid will deform into two types that is major strain (ε_1) and minor strain (ε_2). The example of these two strains is shown in Figure 2.8.

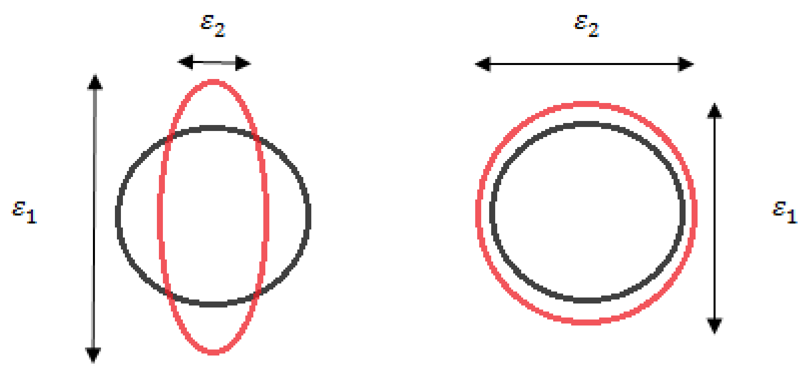


Figure 2.9: Circle grid before and after deformation: (a) Drawing area; (b) Stretch area

Adapted from: Udomphol, 2007

In figure 2.9, the black circle shows the original shape of circle grid before undergo a deformation while red circle shows the new shape of circle grid after undergo the deformation.

The reading of both major and minor strain in the deep drawing process can be recorded on FLD which can be used to predict the formability of sheet metal.

2.7 PUNCH FORCES

The first deep drawing operation is not a steady-state process. The punch force needs to supply the various types of work required in deep drawing, such as the ideal work of deformation, redundant work, friction work and the work required for ironing. The punch forces can be divided between the first drawing operation and the following drawing operations (Boljanovic, 2004).

2.7.1 First Drawing Operation

In deep drawing process, the first drawing process is very important because the force that has been given by punch is difference to following drawing operations. The first drawing punch forces can be calculated by formula as shown in Equation 2.4.

$$F_p = 1.1k \ln \frac{D_1}{d_{s1}} \quad (2.4)$$

Where,

F_p = Punch forces for first drawing $\left({}^{\mathrm{N}}/_{\mathrm{m}^2}\right)$

D_1 = Initial diameter of blank before drawing process (mm)

d_{s1} = Mean diameter of cup after the first drawing (mm)

d_1 = Inside diameter of cup after the first drawing (mm)

2.7.2 Subsequent Drawing Operation

Subsequent drawing operations are different from the first drawing operation because in deep drawing process, the flange diameter will decrease however the zone of plastic deformation does not change due to steady-state process. The punch force for the next drawing operation can be calculated as in Equation 2.5.

$$F_i = \pi d_i t(UTS)\left[\frac{D_1}{d_i} - 0.7\right] \quad (2.5)$$

Where,

F_i = Punch forces for subsequent drawing $({}^{\mathrm{N}}/_{\mathrm{m}^2})$

d_i = Punch diameter (mm)

D_1 = Blank diameter (mm)

t = Material thickness (mm)

2.8 FRACTURE IN DEEP DRAWING

Shell fracture is one of the outcomes commonly observed in deep drawing process. Shell fracture is a fracture that occur on the cup on the sheet metal or blank after through the deep drawing process. Shell fracture in deep drawing is caused by excessive punch load on the blank that has resulted from several factors like excessive punch force (BHF), excessive blank holder force, excessive friction between blank and punch, insufficient clearance between punch and die and insufficient punch or die corner radius. An example of shell fracture is shown in Figure 2.10.

Figure 2.10: Shell fracture of sheet metal after went through deep drawing process.

Source: Yoshihara et al., 2005

Excessive punch force would result in shell fracture directly as it increase the load on the blank, causing the shell to tear or fracture once it exceeds the material plastic limit. Thus, the determination of the suitable punch force is crucial to ensure sufficient force is provided for a given deep drawing operation, and yet not too high to cause fracture. From the previous studies that has been studied by Korhenen (1982), it is can be calculated the maximum drawing force as shown in Equation 2.6. It was observed that for a constant thickness, the required punch force increases when the punch diameter is increase. The punch and die corner radius does not affect the maximum punch force significantly if they are at least 10 times greater than the blank thickness. The fracture toughness and allowable flaw size of materials is decreases with the increases of the materials yield strength (Hertzberg, 1996).

$$F = \left(\frac{1+R}{\sqrt{1+2R}}\right)^{1+n} \times UTS \times \pi D_1 \times t \qquad (2.6)$$

Where,

F = Maximum drawing force $\left(\mathrm{N}/_{\mathrm{m}^2}\right)$

R = Strain ratio

D_1 = Blank diameter before drawing process (m)

n = Strain hardening coefficient

t = Blank thickness (m)

Besides that, excessive BHF will also result in shell fracture as it would result in excessive friction between blank and die, which would increase the punch load causing the shell fracture as it exceeds its plastic limit. Figure 2.11 simplified the effect of BHF in deep drawing process as it is exceeds or insufficient due to displacement of punch.

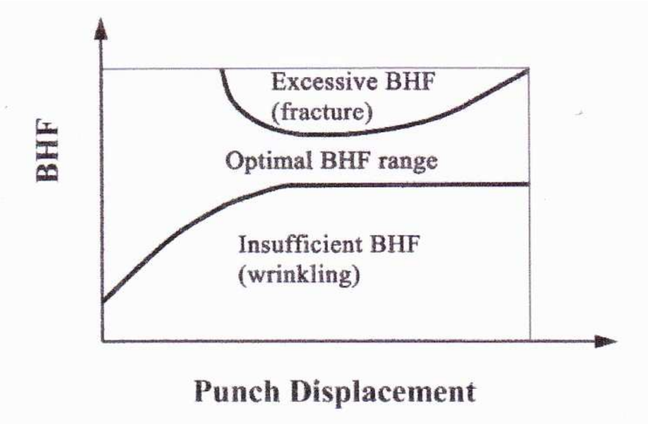


Figure 2.11: Effect of BHF in deep drawing

Source: Obermeyer and Majlessi, 1998

As for the punch and die corner radius, it can be sees that too small of a punch or die corner radius, R_i will cause excessive thinning and tearing at the bottom of the cup (Rao, 1999). If the radii are too small, the required force to draw the blank will be increased. This causes the tensile stresses in the radial direction on the cup wall to increase until a certain extent where it will cause the cup to tear at the critical region, which is at the bottom corner of the cup. Hence, it is customary to provide punch corner radius of 4 – 10 times of blank thickness.

Furthermore, the LDR also one of the main factor that causes the fracture of cup in deep drawing process. This is because of punch-to-blank diameter ratio exceeds the LDR for the material in a single draw. This is due to the fact that deep drawing is independent on the ductility of the blank, which is affected by the amount of strain.

When the fracture of shell happen, the other defects which is occur in deep drawing process also will happen (Moshksar and Zamanian, 1997). The fracture due to excessive drawing speed is caused by inadequate flow of material in the deep drawing pocess. However, too low of a drawing speed will result in reduced the production rate. From previous studies, Browne and Hillary (2003) used drawing speeds of 0.1 – 0.3 m/min for drawing of C.R.1 steel cups of 39.3mm diameter using blanks of 72.28mm diameter and 0.9mm thick.

2.9 DEFECTS IN DEEP DRAWING

In deep drawing process, there are several defects which is occurred after the deep drawing process like wrinkling, earing, excessive thinning of cup and rupture of the blank. The defects usually occur due to unsuitable or non-optimal variables in deep drawing process. Thus, in the designing the deep drawing die and run the experiment, these defects which is occur must be avoided in order to take an ideal result from the experiment.

2.9.1 Wrinkling

Wrinkling is one of the major defects that occur in sheet metal forming by conventional deep drawing process. Wrinkling may be a serious obstacle to a successful forming process and to the assembly of parts, and may also play a significant role in the wear of tool. In order to improve productivity and the quality of products, wrinkling must be avoided. Wrinkling is a kind of buckling phenomenon that prevents from forming of the sheet. If the buckling take place in flange area it is well known as well as it is called puckering if take place on the wall of the cup (Ziaeipoor et al., 2008). The schematic diagram in Figure 2.12 shows the mechanism of wrinkling initiation and growth in the cylindrical cup deep drawing process and Figure 2.13 shows example of wrinkling after deep drawing test.

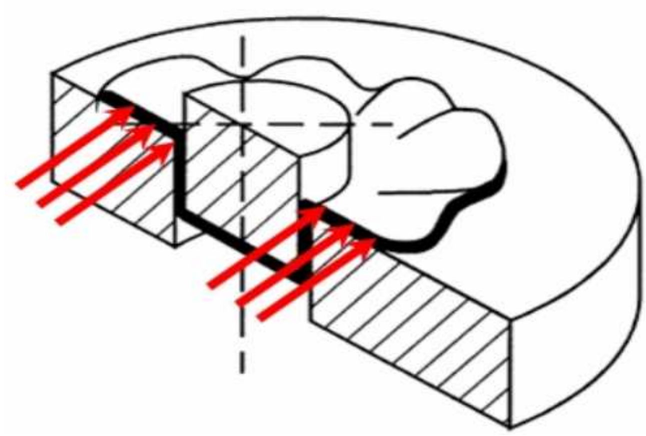


Figure 2.12: The mechanism of wrinkling initiation in the flange area of the cup

Source: Ziaeipoor et al., 2008

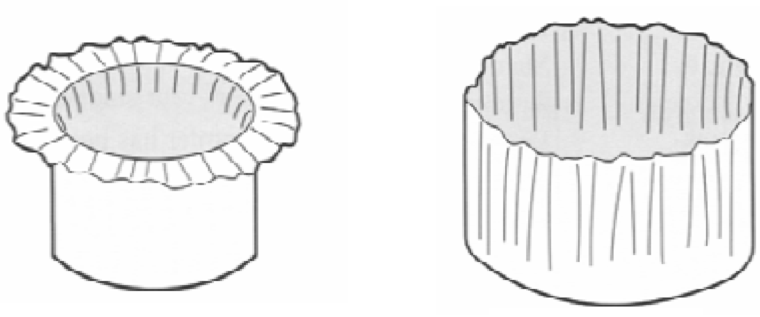
Figure 2.13: Example of wrinkling

Source: Schnakovszky and Ganea, 2007

During the deep drawing process, the sheet under the blank holder is drawn into the deformation zone by the punch. As a result, compressive hoop stress and thus wrinkling can be developed in the sheet metal under the holder (flange wrinkling) as well as those in the side wall, as wrinkling is a phenomenon of compressive instability. The magnitude of the compressive stress necessary to initiate the side- wall wrinkling is usually smaller than that for the flange wrinkling since the wall is relatively unsupported. Hence, the formation of side-wall wrinkles is relatively easier especially when the ratio of the unsupported dimension to sheet thickness is large (Cao and Wang, 1999).

There are several factors that leads to the wrinkling formation like the retaining force of the blank, the geometrical parameters of the die, the frictions that appear during deep-drawing between the blank and the work elements of the die, the material characteristics and anisotropy, the contact conditions, the part geometry, the mechanical properties of the material, the imperfections in the structure and the initial state of internal tensions of the material, etc. (Schnakovszky and Ganea, 2007).

The wrinkling which is occurs in deep drawing process can be divided into two types that is corrugation which is flange instability and bending over that is the instability in the body of the piece. The phenomenon of wrinkling is specific to the process of deep drawing and also depend on the position in the piece in which it occurs.



(a) (b)

Figure 2.14: Wrinkling types: (a) Corrugation; (b) Bending over

Source: Schnakovszky and Ganea, 2007

Usually, the retaining force has to increase along with the increase of the deep drawing depth but it has to take note that if its value is too big it can lead to cracks and even a break of the material. The main geometric parameters of the die which influence the wrinkling is the diameter of the punch. In the case of friction between the piece and the tool, the increase of the coefficient of friction determines the wrinkling to reduce but high value of the coefficient can cause cracks and material breakage (Schnakovszky and Ganea, 2007).

2.9.2 Earing

Earing is one of the defects which is commonly observed in deep drawing process. By definition, earing is uneven height at the edge of a drawn product, forming a series of peak and valleys along its circumference. Kishor and Kumar (2002) defined earing is the formation of waviness on the top of the drawn cup. The numbers of ears formed is commonly four (Hosford and Caddell, 2007), but might also be two, six or eight, depending on thermo-mechanical processing and microstructure of the sheet (Engler and Hirsch, 2007).

Figure 2.15: Earing in deep drawing

Source: Engler and Hirsch, 2007

During deep drawing, the sheet metal is subjected to different amount of plastic strain for each angle relative to rolling direction, which causes different amount of elongation resulting in formation or ears. The difference in amount of elongation resulting in formation of ears. The difference in amount of plastic deformation in different angle is due to anisotropic properties of material. Earing in deep drawing is usually not desirable as the ears serves no purpose and will have to cut off, resulting in loss of material, production rate and increase in production costs (Kishor and Kumar, 2002).